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Resonant Frequency and Radiation Efficiency of Meander Line Antennas

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SUMMARY

One of the approaches to reducing the size of half-wavelength linear dipole antennas is the meander dipole antenna, where the elements form a meander line. This paper presents a formula for the relationship between the geometrical size and the resonant frequency of the meander line dipole antenna, and a calculation formula for the radiative efficiency is derived from the result. It is shown that the geometrical parameters of the meander line dipole antenna can be determined from the specified radiative efficiency. © 1999 Scripta Technica, Electron Comm Jpn Pt 2, 83(1): 52–58, 2000

Key words: Small-sized antenna; dipole antenna; meander; resonant frequency; radiative efficiency.

1. Introduction

It is desirable that antennas for portable information terminals, such as portable phones and the cordless phones, be small and lightweight [1]. Linear antennas such as whip antennas are generally used for portable information terminals because of their simple structure. The antenna length is reduced by bending the linear antenna into a spiral [2] or a meander [3], or by top-loading. Generally, when the size of the antenna is reduced, the radiative resistance is reduced. This results in the problem of decreased radiative efficiency because the ratio of the ohmic loss of the antenna conductor to the radiated power is increased [4].

In designing linear antennas with complex shape, simulations of the impedance or the radiative characteristics have been performed by the method of moments [5] and other methods. To arrive at optimal parameters, however, such numerical computations must be iterated. Because of this situation, there is a need for a design method by which the optimal parameters of the antenna can be determined simply, taking into consideration the antenna characteristics, such as resonant frequency and radiative efficiency.

One method of reducing the size of the dipole antenna is the meander line dipole antenna (MDA) [6], in which the radiating part of the linear dipole antenna is bent to a meander to reduce the antenna length. This antenna has the feature that the antenna length is reduced and the antenna can be implemented on a plane. It is not easy, however, to determine the optimal parameters because the parameters must be considered in the design.

This paper derives a formula to represent the relationship between the resonant frequency and various geometrical parameters. In this approach, the meander part of the MDA is considered as the load. The meander part is considered as consisting of short-terminated, parallel, two-wire lines whose length is much shorter than the wavelength of the frequency employed. In other words, a model consisting of a linear dipole antenna with inductance loading is considered. The formula for the radiative efficiency of the MDA is derived from the relationship between the antenna length and the radiative resistance. Using these two formulas, the geometrical parameters of the antenna are related to the resonant frequency and the radiative efficiency.

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As the first step, Section 2 models the MDA as a linear dipole antenna that has inductance loading. The inductance is calculated using the geometrical parameters of MDA. A formula for the relationship between the inductance and the resonant frequency is derived, and an experimental formula for the relationship between the geometrical parameters and the resonant frequency is derived. Based on the formula for the relationship between the antenna length and the radiative resistance, a formula for calculating the radiation efficiency is derived in terms of the geometrical parameters.

Section 3 uses the relationship between the geometrical parameters and the resonant frequency as well as the formula for calculating the radiative efficiency in terms of the geometrical parameters derived in Section 2. Then, the actual radiative efficiency of the MDA is calculated. By comparing the calculated results to the measurements, the validity of the proposed method is verified. Then, it is shown that the optimal parameters of the MDA can be determined by considering the radiative efficiency when the resonant frequency, the antenna length, and the antenna width are specified.

2. Design Procedure

2.1. Configuration and Modeling of the MDA

Figure 1 shows the configuration of the MDA, and Table 1 shows the structural parameters. The element conductor is assumed to be cylindrical. In this paper, the MDA of Fig. 1 is modeled as a linear dipole antenna with inductive loading. The antenna is decomposed into short-terminated transmission lines, whose number $2N$ is equal to the number of turns of the antenna, and a linear circular cylindrical conductor whose length is equal to the antenna length $2l$.

In Fig. 2, the characteristic impedance Z_0 of the short-terminated line in Fig. 2 is given by [7] as

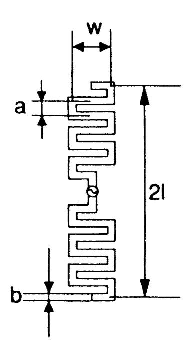

Fig. 1. Configuration of meander line dipole antenna.

Table 1. Configuration of MDA

Antenna width	w
Antenna length	$2l$
Pitch	a
Conductor diameter	b
Number of turns	$2N$

$$Z_0 = \frac{Z_c}{\pi} \log \frac{2a}{b} \tag{1}$$

where Z_c is the intrinsic impedance. When the short-terminated line is lossless, the input impedance Z_{in} of the short-terminated line is a pure reactance jX.

$$Z_{in} = jX = jZ_0 \tan \beta \frac{w}{2} \tag{2}$$

Suppose that the length of the short-terminated line i.e., the half-width of the antenna ($w/2$), is sufficiently small compared to the wavelength. Forming the series expansion and retaining terms up to third order, we obtain

$$\tan \beta \frac{w}{2} = \beta \frac{w}{2} + \frac{1}{3}\left(\beta \frac{w}{2}\right)^3 \tag{3}$$

Let the total inductance of all short-terminated lines shown in Fig. 2, i.e., the meander part, be L_m. Then, it follows from Eqs. (1)–(3) that

$$j\omega L_m \equiv 2N \cdot Z_{in} = 2N \cdot jZ_0 \left(\beta \frac{w}{2} + \frac{1}{3}\left(\beta \frac{w}{2}\right)^3\right) \tag{4}$$

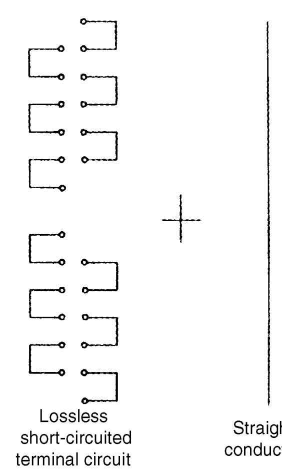

Fig. 2. Analytical model.

$$\therefore L_m = \frac{NZ_0 w}{c}\left(1+\frac{1}{3}\left(\beta\frac{w}{2}\right)^2\right)$$

$$= \frac{\mu}{\pi}Nw\log\frac{2a}{b}\left(1+\frac{1}{3}\left(\beta\frac{w}{2}\right)^2\right) \quad (5)$$

The self-inductance of a linear conductor of length $2l$ of Fig. 2 with those inductances as the loading is given by [8]

$$L_l = \frac{\mu}{\pi}l\left(\log\frac{8l}{b}-1\right) \quad (6)$$

Then, the total inductance L_t of the conductors forming the MDA is

$$L_t = L_m + L_l$$

$$= \frac{\mu}{\pi}\left\{l\left(\log\frac{8l}{b}-1\right)+Nw\log\frac{2l}{Nb}\left\{1+\frac{1}{3}\left(\beta\frac{w}{2}\right)^2\right\}\right\}$$

$$\left(\because a = \frac{l}{N}\right) \quad (7)$$

2.2. Equation for frequency versus structure parameter

The dipole antenna near the resonant frequency can be represented by an equivalent circuit consisting of a series connection of a capacitance and an inductance. In the case of an MDA, the inductance given by Eq. (5) in the previous section is included in the inductance of the equivalent circuit. The capacitance of the meander part is considered the static capacitance between the two lines as given by Eq. (1) in the short-terminated, transmission-line model.

This section considers the inductance in the equivalent circuit which is valid near the resonant frequency and derives a formula for the relationship between the resonant frequency and the geometrical parameters. For a linear dipole antenna that resonates at the same frequency f (GHz) as the MDA, the self-inductance L_d of the conductor is given as follows, where λ is the wavelength for f (GHz):

$$L_d = \frac{\mu}{\pi}\frac{\lambda}{4}\left(\log\frac{2l}{b}-1\right) \quad (8)$$

Because it is assumed that the MDA with the self-inductance L_t and the linear dipole antenna with the self-inductance L_d have the same resonant frequency, we can write, approximately,

$$L_d \fallingdotseq L_t \quad (9)$$

Several kinds of MDAs were constructed, and the L_t and L_d were examined. The results verified that Eq. (9) is approximately valid.

The following transcendental equation for the number of turns N is derived from Eqs. (7) and (8):

$$N = \frac{\frac{\lambda}{4}\left(\log\frac{2\lambda}{b}-1\right)-l\left(\log\frac{8l}{b}-1\right)}{w\log\frac{2l}{Nb}\left(1+\frac{1}{3}\left(\beta\frac{w}{2}\right)^2\right)} \quad (10)$$

The number of turns can be determined by Eq. (10) when the antenna length l, the antenna width w, the conductor diameter b, and the resonant frequency f are specified.

In the series expansion in Eq. (3), terms of up to third order are considered. When only the first-order term is considered, we obtain

$$N = \frac{\frac{\lambda}{4}\left(\log\frac{2\lambda}{b}-1\right)-l\left(\log\frac{8l}{b}-1\right)}{w\log\frac{2l}{Nb}} \quad (11)$$

The ratio b/a of the conductor width and the pitch is given three values 0.25, 0.50, and 0.75, and the solutions N of transcendental Eqs. (10) and (11) are calculated while varying the antenna width w. Figure 3 shows the calculated results. By comparing the two solutions, we see that almost the same results are obtained.

The condition for the series expansion in Eq. (3) implies that

$$\left|\beta\frac{w}{2}\right| < \frac{\pi}{2}$$

$$\therefore w < \frac{\lambda}{2} \quad (12)$$

Because the antenna width w cannot be larger than the wavelength of the applied frequency, the transcendental equations can be used for the antenna width within the range considered in the design.

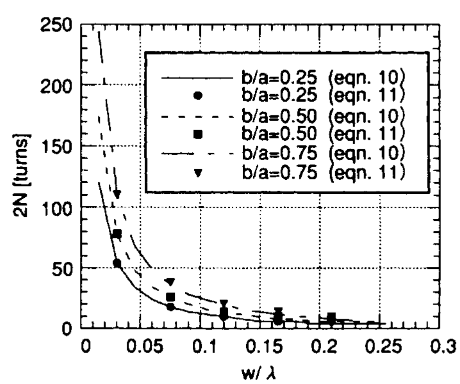

Fig. 3. Antenna width and number of turns ($2l/\lambda = 0.10$).

As a result of these investigations, transcendental Eq. (11) is used, and its validity is examined as follows. For a meander line monopole antenna composed of flat conductors, the resonant frequency is actually measured as a function of the conductor width/pitch. It is also calculated using Eq. (11). The results are shown in Fig. 4. The calculation is done by replacing the flat conductor by the equivalent cylindrical conductor [9]. In the experimental measurements, the antenna length and the number of turns are kept constant. The measured and calculated values closely agree (Fig. 4), indicating the validity of Eq. (11).

When only the first-order term is retained, Eq. (2) becomes

$$Z_{in} = jZ_0 \tan\beta\frac{w}{2} \cong jZ_0\beta\frac{w}{2} \tag{2'}$$

where β is the phase constant. Let the characteristic impedances of the short-terminated line in free space and the dielectrics be Z_0 and Z_0', respectively. Let the phase constants be β, β′ and the wavelengths be λ_0, λ_g, respectively. Then,

$$Z_0'\beta' = Z_0'\frac{2\pi}{\lambda_g} = Z_0\frac{2\pi}{\lambda_0} = Z_0\beta$$

and Eq. (2′) is valid regardless of the medium.

2.3. Formula for radiative efficiency

For the MDA shown in Fig. 1, the total length $2l_t$ along the elements is represented as follows in terms of the geometrical parameters:

$$\begin{aligned} l_t &= l + Nw \\ &\cong Nw \quad (N >> 1) \end{aligned} \tag{13}$$

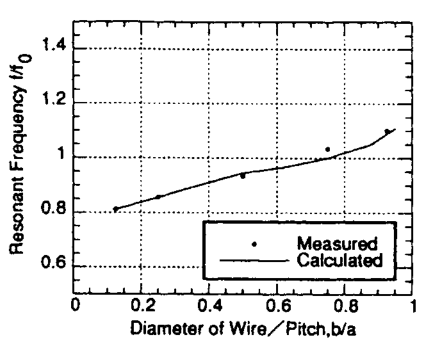

Fig. 4. Resonant frequency of MDA calculated and compared with measurements ($a/\lambda = 0.018$, $W/\lambda = 0.03$, $l/\lambda = 0.144$).

Suppose that the current is distributed on the conductor in sinusoidal form. Then, the current is represented as follows:

$$I(z) = I_0 \sin k'(l_t - |z|) \quad \left(k'l_t = \frac{\pi}{2}\right) \tag{14}$$

It is assumed that the current is distributed uniformly along the periphery of the conductor. Z is the coordinate along the conductor.

Letting the skin resistance of the conductor be R_S, the conductor loss P_C of the conductor composing the antenna is given by

$$P_c = R_s \frac{l_t}{\pi b} I_0^{\ 2} \tag{15}$$

Letting the radiative loss of the antenna be P_r,

$$P_r = R_r I_0^{\ 2} \tag{16}$$

where R_r is the radiative resistance.

Thus, the radiative efficiency η is given by

$$\eta = \frac{P_r}{P_r + P_c} = \frac{1}{1 + \frac{R_s}{R_r}\frac{l_t}{\pi b}} \cong \frac{1}{1 + \frac{R_s}{R_r}\frac{Nw}{\pi b}} \tag{17}$$

For the MDA, the relationship between the reduction ratio of the antenna length compared to the linear dipole antenna and the reduction ratio of the radiative resistance is examined. The reduction ratio of the antenna length R_e and the reduction ratio of the radiation resistance r are defined as follows:

$$\left.\begin{aligned} R_e &\equiv \frac{2l}{\lambda/2} \\ r &\equiv \frac{R_r}{R_d} \end{aligned}\right\} \tag{18}$$

where R_d is the radiative resistance of the half-wavelength dipole antenna.

Figure 5 shows the measured relationship between the reduction ratio of the antenna length and the reduction ratio of the radiative resistance for several kinds of MDAs. The dashed line in the figure is the line for $r/R_e = 1$. Figure 5 shows that the measured values closely agree with the line $r/R_e = 1$ in the range of the decreasing ratio of the antenna length 0.4 to 0.7. In other words,

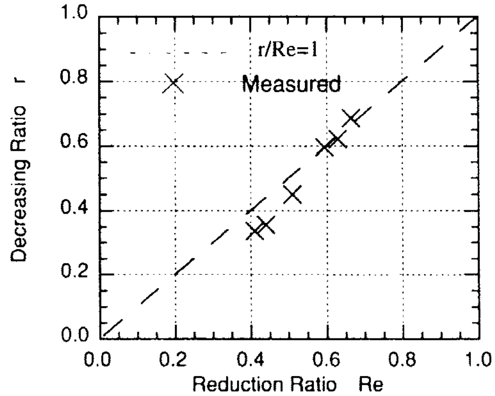

Fig. 5. Reduction ratio of MDA and 1/2 wavelength dipole antenna and decreasing ratio of radiative resistance.

$$R_r = R_d \frac{4l}{\lambda} \tag{19}$$

The following relationship is obtained from Eqs. (17) and (19):

$$\eta = \frac{1}{1 + \dfrac{1}{4\pi}\dfrac{R_s}{R_d}\dfrac{\lambda}{b}\dfrac{Nw}{l}} \tag{20}$$

Thus, when the geometrical parameters and the resonant frequency of the MDA are specified, the radiative efficiency can be determined from Eq. (20).

3. Example of Calculating the Number of Turns and Radiative Efficiency

For an MDA composed of a flat conductor, the antenna length $2l$ is kept constant. The radiation efficiency η and the number of turns $2N$ are calculated as functions of the ratio b/a of the conductor width and pitch. Three kinds of antennas are considered, keeping the antenna width w and the antenna length as constants. Figures 6 and 7 show the calculated results. The skin resistance R_s of the conductor in Eq. (15) is given by

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \tag{21}$$

where $\omega(= 2\pi f)$ is the angular frequency, μ is the permeability, and σ is the conductivity. Copper is assumed as the conductor in the calculation.

The figure shows that there exists a maximum in the radiative efficiency when the ratio b/a of the conductor width and pitch is gradually increased. The reason is as follows. When b/a is small, the conductor width is reduced, and the conductor loss is increased. But when b/a is large, the required number of turns is increased, as is seen from Fig. 7, which increases the conductor loss. The measured values are also shown in the figures. The radiative efficiency does not include mismatch loss. The calculation and the measurements agree well in both figures, indicating the validity of the proposed method.

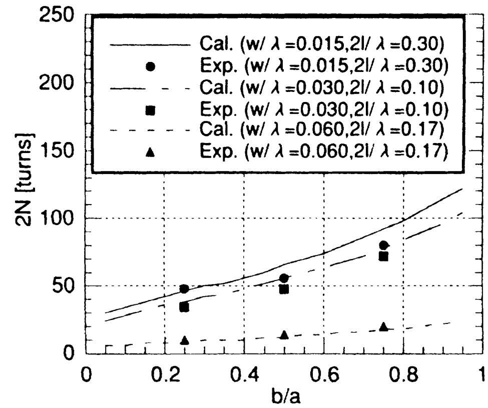

Fig. 6. Radiative efficiency calculated and compared with measurements.

As the next step, the MDA composed of a flat conductor is reconsidered. By specifying the antenna width w, the resonant frequency f, the ratio b/a of the conductor width and the pitch, and the antenna length $2l$, the number of turns $2N$ of the meander part and the radiative efficiency η are calculated. The result is shown in Fig. 8. The measured values are also shown in the figure. The figure shows that when the size of the antenna is reduced, the radiative

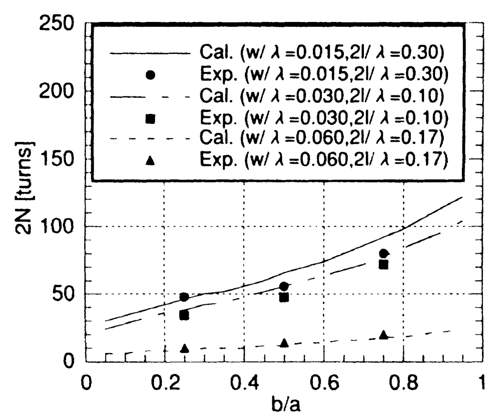

Fig. 7. The number of turns calculated and compared with measurements.

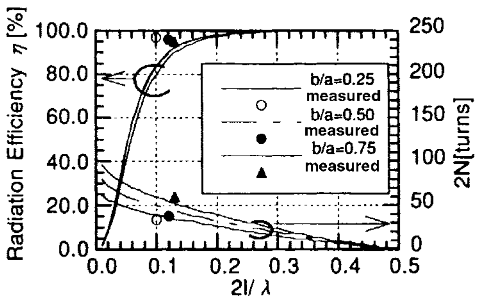

Fig. 8. Radiative efficiency and number of turns ($w/\lambda = 0.030$).

efficiency η decreases, and a larger number of turns $2N$ is required. Assume that this figure is prepared beforehand, along with the design chart. Let it be specified, for example, that the width w is 0.03, the ratio b/a of the conductor width and the pitch is 0.25, and the radiative efficiency η is 80% for the antenna to be designed. Then, it follows from Fig. 8 that the antenna length $2l$ is 0.1λ and the number of turns is 42.

4. Conclusions

This paper has considered the MDA as an approach to reducing the size of linear dipole antennas, in which radiating elements are bent in a meander form. A formula representing the relationship between the structural parameters and the resonant frequency is derived. Then, the formula for the relationship between the reduction ratio of the antenna length and the reduction ratio of the radiative resistance is used to derive a formula for the radiative efficiency. Using these formulas, the relationship between the structural parameters and the radiative efficiency is derived, and a design procedure for the MDA is presented.

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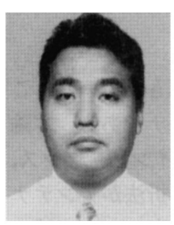

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